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Research article
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Effect of hot deformation and heat treatment conditions on the structure and mechanical properties of the VIT1 alloy based on orthorhombic titanium aluminide

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Abstract: The effect of thermo-mechanical treatment on the structure and mechanical properties of the hot-rolled orthorhombic titanium aluminide alloy VIT1 was investigated. The evolution of the microstructure and mechanical behavior of the alloy during hot deformation in the temperature range of 850–1050 °C was studied. It was established that at a temperature of 950 °C, a strain rate of $\dot{\varepsilon} = 5 \cdot 10^{-4}$ s^{-1} and a strain of $\varepsilon = 70$ %, the microstructure formed during hot deformation, due to the processes of recrystallization and spheroidization, consisted of grains ~1 μm in size, comprising β-, α_2-, and O-phases. It was shown that increasing the deformation temperature led to the dissolution of O-phase particles and a significant deceleration in the development of dynamic recrystallization. Homogeneous fine-grained billets were obtained via multi-directional isothermal forging, and the effect of heat treatment (quenching and aging) on the structure and mechanical properties of the alloy was examined. Based on a preliminary study of the influence of heating temperature on the alloy's structure and properties, the temperature ranges for quenching and aging were determined. It was demonstrated that the most balanced levels of strength, ductility, and heat resistance were achieved after heat treatment under the following conditions: holding for 4 h at 1025 °C followed by air cooling, and aging at 850 °C for 6 h.

Keywords: orthorhombic titanium aluminide Ti_2NbAl, VIT1 alloy, multi-directional isothermal forging, quenching, aging, mechanical properties.

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Влияние режимов горячей деформации и термической обработки на структуру и механические свойства сплава на основе орторомбического алюминида титана ВИТ1

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Аннотация: Исследовано влияние деформационно-термической обработки на структуру и механические характеристики сплава на основе орторомбического алюминида титана ВИТ1 в горячекатаном состоянии. Проведено изучение эволюции микроструктуры и механического поведения сплава при горячей деформации в температурном интервале 850–1050 °С. Установлено, что при температуре t = 950 °С, скорости деформации $\dot{\varepsilon} = 5 \cdot 10^{-4}$ с$^{-1}$ и степени деформации ε = 70 % в сплаве, вследствие протекания при горячей деформации процессов рекристаллизации и сфероидизации, формируется микроструктура с размером зерен ~1 мкм, состоящая из β-, α_2- и О-фаз. Показано, что повышение температуры деформации ведет к растворению частиц О-фазы и резкому замедлению развития динамической рекристаллизации. Всесторонней изотермической ковкой получены заготовки с однородной мелкозернистой структурой и исследовано влияние термической обработки (закалки и старения) на структуру и механические свойства сплава. По результатам предварительного изучения влияния температуры нагрева на структуру и свойства сплава определены интервалы температур закалки и старения. Показано, что наиболее сбалансированный уровень прочности, пластичности и жаропрочности получен после термической обработки при следующих условиях: выдержка 4 ч при t = 1025 °С с последующей закалкой на воздухе, старение 850 °С в течение 6 ч.

Ключевые слова: орторомбический алюминид титана Ti_2NbAl, сплав ВИТ1, всесторонняя изотермическая ковка, закалка, старение, механические свойства.

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Introduction

The intermetallic alloy VIT1 (density ρ ~ 5.3 g/cm^3) based on orthorhombic titanium aluminide Ti_2NbAl was developed at FSUE "VIAM" (Moscow, Russia) [1]. It is characterized by high specific properties, an operating temperature of up to 700 °C, and is considered a promising material for high-pressure compressor (HPC) blades in modern gas turbine engines [1; 2]. Alloys based on Ti_2NbAl are deformable and undergo hot forging and/or rolling in the single-phase β-region [3–7]. In the as-cast state, the alloy exhibits extremely low ductility [1]. Hot forging or rolling in the β-, followed by the (β + α_2)-phase regions significantly refines the struc-

ture, which simultaneously enhances both ductility and strength [3]. For example, a notable improvement in these properties was achieved in the Ti—20.3Al—22.1Nb—1.2Zr—1.3V—0.9Mo—0.3Si alloy through multi-directional isothermal forging, resulting in a submicron grain/particle size of 0.3 μm and achieving ultimate tensile strength σ_u = 1400 MPa and elongation δ = 25 % [8]. The grain refinement effect is retained during heat treatment. In the VTI-4 alloy, after forging and rolling in the ($\beta + \alpha_2$)-phase region, followed by a two-step heat treatment (1025 °C quenching in oil + + 750 °C for 3 h with air cooling), satisfactory values of σ_u = 1081 MPa and δ = 7.2 % were obtained [9]. In the Ti—22Al—27Nb alloy, reducing the β-grain size from 200 to 5 μm through hot rolling in the ($\beta + \alpha_2$)-phase region and subsequent heat treatment (heating to the ($\beta + \alpha_2$)-phase region followed by furnace cooling) increased the σ_u from 900 to 1050 MPa and the δ from 5 % to 15 % [5].

It is important to emphasize that grain refinement in orthorhombic titanium aluminide alloys leads to reduced creep resistance [9]. Therefore, when determining their mechanical properties, it is essential to balance strength, ductility, and heat resistance. However, systematic studies in this direction are practically absent. The formation of a fine-grained structure also significantly enhances the hot ductility of these alloys, which can be utilized in the manufacturing of complex-shaped components.

Another equally important microstructural parameter is the size of the O-phase particles, which form during the aging of quenched alloys and significantly affect their mechanical characteristics [10—13]. For instance, it was shown in [11] that increasing the aging temperature from 750 to 850 °C led to an increase in elongation from 0.4 % to 5.0 %, while the yield strength decreased from 1295 to 960 MPa. However, the literature lacks systematic data that could recommend specific conditions of deformation and heat treatment for orthorhombic titanium aluminide alloys to achieve a high combination of mechanical properties. In this regard, the aim of the present study was to develop processing conditions for structure refinement through isothermal forging and heat treatment of the VIT1 alloy to ensure a balance of strength, ductility, and heat resistance.

Materials and methods

The material studied was a 35-mm-thick hot-rolled plate of the VIT1 alloy, based on orthorhombic titanium aluminide. Isothermal uniaxial compression tests were conducted at temperatures of 850, 900, 950, 1000, and 1050 °C and a strain rate of $\dot{\varepsilon} = 5 \cdot 10^{-4}$ s^{-1}. Specimens with a diameter of 10 mm and a height of 15 mm were cut from the plate parallel to the rolling direction using wire electrical discharge machining. The tests were performed on an Instron 300LX universal testing machine. The specimens were placed in a furnace preheated to the deformation temperature, held for 10 min, deformed to a strain of ε = 70 %, and then quenched in water.

Billets measuring 35×40×100 mm, cut from the plate in the rolling direction, were annealed at 1100 °C for 0.5 h. Subsequently, multi-directional isothermal forging was performed at 950 °C on a DEVR 400 press equipped with a die block, with final-stage upsetting [14]. The initial strain rate was ~10^{-3} s^{-1}, and the total strain was — ε_Σ = 750 %. As a result, forgings with dimensions of 120×120×14 mm were obtained.

For heat treatment, specimens with dimensions of 5×5×5 mm were cut. Quenching was carried out after a 2-hour hold at 950—1100 °C, followed by water cooling. Aging was conducted at 750, 800, 820, and 850 °C for holding times of 0.5, 1, 2, 4, 6, 8, 12, 24, 48, 96, and 192 h.

The microstructure was evaluated using a scanning electron microscope (SEM) FEI Quanta 600 and a transmission electron microscope (TEM) Jeol JEM-2100. Electron backscatter diffraction (EBSD) mapping was performed using the TSL Data Collection version 6.2 software, with a scanning step of 100 nm. Data processing was carried out using TSL OIM Analysis version 6. The volumetric phase fraction was determined from SEM images according to ASTM E562-11, and the fraction of recrystallized grains was evaluated from EBSD data. TEM foils were prepared at –35 °C using an electrolyte consisting of methanol (60 %), butanol (34 %), and perchloric acid (6 %). The Vickers microhardness was measured using a Wolpert 402MVD hardness tester, following GOST 9450-76. The measurements were taken using a diamond pyramid with a base angle of 136° under a load of 500 g and a dwell time of 10 s.

For tensile testing, cylindrical specimens were prepared in accordance with GOST 1497-84, with a gauge section diameter of 3 mm and a length of 15.35 mm, and tested on an Instron 5882 machine at an initial strain rate of 10^{-3} s^{-1}. Creep tests were conducted on cylindrical specimens prepared according to GOST 10145-81, with a gauge section diameter of 5 mm and a length of 27 mm, using an ATS Creep Tester 2330 machine. Three thermocouples were attached to the specimen to monitor temperature, and an extensometer was installed to record elongation. The specimens were heated at a rate of 550 °C/h to

650 °C, held for 30 min, and then automatically loaded to a stress of 380 MPa.

Results and discussion

Fig. 1 shows the initial microstructure of the hot-rolled VIT1 alloy plate. The microstructure consists of β-grains elongated along the rolling direction, with an average length and width of approximately 500 μm and 150 μm, respectively (Fig. 1, *a*, *c*). Particles of the α_2-phase, averaging 3 μm in size, are predominantly located along the grain boundaries (Fig. 1, *a*, *b*). Electron diffraction patterns obtained via TEM also revealed the presence of needle-shaped O-phase particles with an average diameter of 200 nm and lengths ranging from 0.2 to 3 μm (Fig. 1, *d*).

To determine the optimal conditions for isothermal forging, the effect of deformation temperature on the mechanical behavior and structural evolution during uniaxial compression was studied. In specimens cut from the plate, the elongated grains formed during rolling were oriented parallel to the deformation axis (Fig. 1, *c*). At t = 850 °C, the σ–ε curve exhibits a peak followed by a sharp softening (Fig. 2), indicating the development of dynamic recrystallization (Fig. 3) and likely the localization of plastic deformation. With a further increase in temperature to 950 °C, the peak stresses decrease, and the steady-state plastic deformation stage becomes more prolonged. At t = 975÷1050 °C, the curves show no initial strengthening during flow, and a slight increase in stress with strain is attributed to the frictional contribution at the specimen surface.

After the tests, the specimens were cut along the deformation axis for further microstructural analysis. The microstructure of the deformed alloy at t = 850 °C is shown in Fig. 3, *a*. During deformation, recrystallization occurs in the β-phase, accompanied by spheroidization of O- and α_2-phase particles [15], resulting in the formation of a fine-grained structure in the central part of the specimen (Fig. 3, *a*). The average grain/particle size was 0.5 μm. Increasing the deformation temperature to 900 °C led to an increase in grain/particle size to 0.6 μm (Fig. 3, *b*).

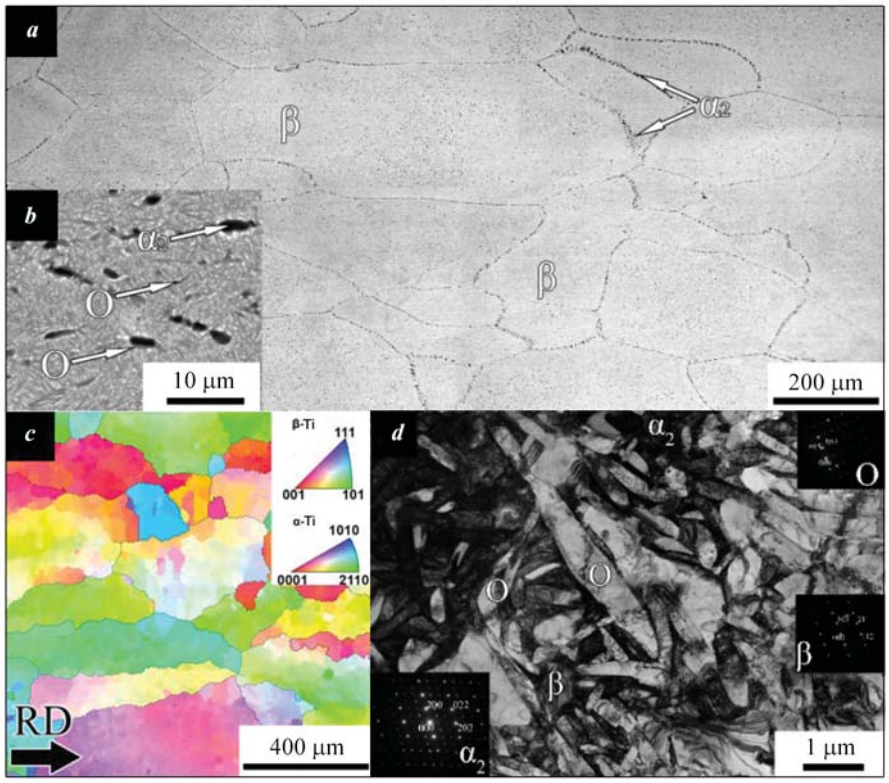

Fig. 1. Microstructure of the hot-rolled VIT1 alloy plate

a – overview SEM image; ***b*** – magnified SEM section; ***c*** – inverse pole figure map, with the rolling direction indicated by an arrow; ***d*** – electron diffraction patterns of the β-, α_2-, and O-phases

Рис. 1. Микроструктура горячекатаной плиты сплава ВИТ1

a – обзорный снимок СЭМ; ***b*** – увеличенный участок структуры СЭМ; ***c*** – карта обратных полюсные фигур, стрелкой показано направление прокатки; ***d*** – ПЭМ-картины электронной дифракции β-, α_2- и O-фаз

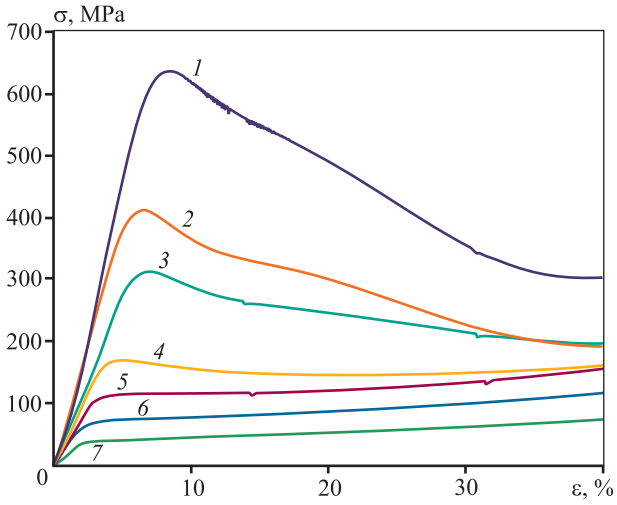

Fig. 2. σ–ε curves of the VIT1 alloy at $t = 850 \div 1050$ °C and $\dot{\varepsilon} = 5 \cdot 10^{-4}$ s^{-1}

t, °C: ***1*** – 850, ***2*** – 900, ***3*** – 925, ***4*** – 950, ***5*** – 975, ***6*** – 1000, *7* – 1050

Рис. 2. Кривые σ–ε сплава ВИТ1 при $t = 850 \div 1050$ °C и $\dot{\varepsilon} = 5 \cdot 10^{-4}$ с$^{-1}$

t, °C: ***1*** – 850, ***2*** – 900, ***3*** – 925, ***4*** – 950, ***5*** – 975, ***6*** – 1000, *7* – 1050

An important factor influencing structural evolution is the phase composition of the alloy and its changes during heating (Fig. 4). As the temperature increases from 850 to 900 °C, the volume fraction ratio of O- and β-phases changes slightly: the O-phase fraction decreases from 86 to 73 vol. %, while the β-phase fraction increases from 13 to 24 vol. % and the α_2-phase fraction from 1 to 3 vol. %. The microstructure of the alloy after deformation at $t = 950$ °C is characterized by significantly larger β-phase grains (2 μm), with O-phase (1 μm) and α_2-phase particles (1.5 μm) located both within the grains and along their boundaries (Fig. 3, *c*). The volume fraction of the O-phase decreases significantly to 22 vol. %, accompanied by an increase in the β-phase fraction to 75 vol. % and the α_2-phase fraction to 13 vol. % (Fig. 4).

The microstructural study using EBSD analysis revealed that during deformation, the initial grains align along the metal flow direction, forming a texture that becomes sharper at lower temperatures (Fig. 4). It can be observed that at $t = 950$ °C, the main structural chang-

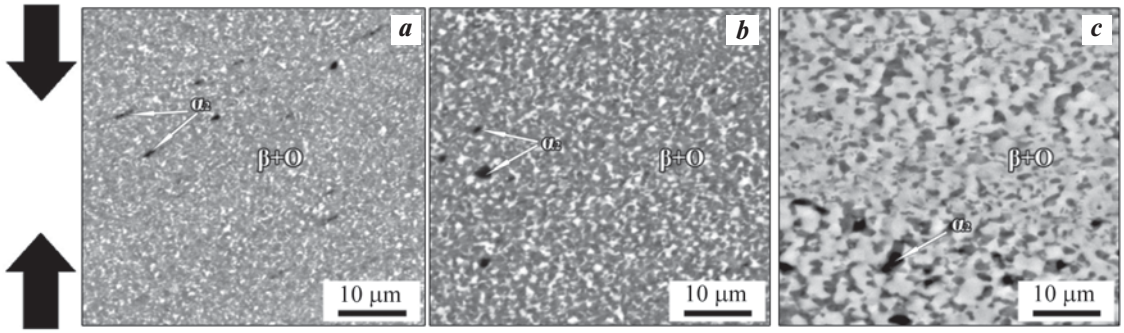

Fig. 3. Microstructure of the VIT1 alloy after deformation (SEM)

t, °C: ***a*** – 850, ***b*** – 900, ***c*** – 950; $\dot{\varepsilon} = 5 \cdot 10^{-4}$ s^{-1}; ε = 70 %. The deformation axis is oriented vertically

Рис. 3. Микроструктура после деформации сплава ВИТ1 (СЭМ)

t, °C: ***a*** – 850, ***b*** – 900, ***c*** – 950; $\dot{\varepsilon} = 5 \cdot 10^{-4}$ с$^{-1}$; ε = 70 %. Ось деформации ориентирована вертикально

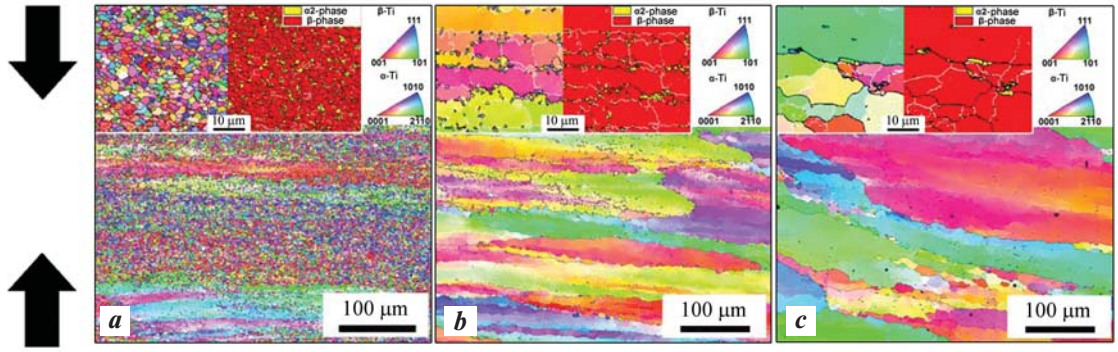

Fig. 4. Microstructure of the VIT1 alloy after deformation (EBSD IPF maps)

t, °C: ***a*** – 950, ***b*** – 975, ***c*** – 1000; $\dot{\varepsilon} = 5 \cdot 10^{-4}$ s^{-1}; ε = 70 %. The deformation axis is oriented vertically

Рис. 4. Микроструктура после деформации сплава ВИТ1 (EBSD IPF-карты)

t, °C: ***a*** – 950, ***b*** – 975, ***c*** – 1000; $\dot{\varepsilon} = 5 \cdot 10^{-4}$ с$^{-1}$; ε = 70 %. Ось деформации ориентирована вертикально

es occur predominantly within the original β-grains, which exhibit highly curved boundaries due to their migration (Fig. 4, *a*).

A further increase in the deformation temperature to 975 °C leads to the complete dissolution of O-phase particles, an increase in the β-phase fraction (89 vol. %), and a reduction in the α_2-phase fraction (11 vol. %) (Fig. 4, *b*). As a result, dynamic recovery dominates during deformation, with only slight curvature observed at some boundaries and the appearance of new recrystallized grains, approximately 10 μm in size. The average size of the large elongated β-phase grains is 160×30 μm, which is significantly smaller than in the initial state. The size of the α_2-phase particles remains unchanged at 1.5 μm. Thus, the dissolution of O-phase particles, a reduction in the α_2-phase fraction, and an increase in temperature significantly suppress dynamic recrystallization in the β-phase, as evidenced by the small number of new grains and the formation of predominantly low-angle boundaries within the original β-grains (Fig. 4, *b*). At a deformation temperature of 1000 °C, the alloy's microstructure consists of relatively large elongated β-phase grains with an average size of 200×70 μm and a small number of equiaxed α_2-phase grains, approximately 2 μm in size (4 vol. %) (Fig. 4, *c*). Further temperature increases lead to a noticeable growth of β-grains.

Thus, the results of the conducted tests demonstrate that deformation of the alloy via uniaxial compression under isothermal conditions can produce a fine-grained structure at a temperature of 950 °C. Lowering the deformation temperature below 950 °C leads to significant localization of plastic deformation, while increasing it results in the complete dissolution of the O-phase, which severely slows the kinetics of dynamic recrystallization and prevents grain refinement. Achieving a uniform fine-grained structure throughout the entire specimen volume requires increasing the degree of deformation during processing, which is possible through multi-directional isothermal forging [8; 14; 16].

An additional effect can be achieved by annealing the billets above the polymorphic transformation temperature, which helps mitigate the inheritance of the rolling texture during subsequent forging. It was observed that heating to 1100 °C and holding for 0.5 h results in the formation of polygonal grains with an average size of 200 μm (Fig. 5, *a*). The annealed billets were subjected to multi-directional isothermal forging at 950 °C [17—19], resulting in a homogeneous microstructure with an average grain/particle size of ~1 μm (Fig. 5, *b*).

As noted earlier, the balance of strength, ductility, and heat resistance in orthorhombic titanium aluminide alloys is determined by a combination of microstructural factors: β-grain size, the dispersion, and volume fraction of strengthening α_2- and O-phase particles. The dispersion and volume fraction of the O-phase are governed by the supersaturation of alloying elements in the β-phase, which depends significantly on the selected quenching temperature. From the results, it is evident that complete dissolution of the O-phase occurs at temperatures above 950 °C. Therefore, potential quenching temperatures are in the range of 975 °C and above. The upper temperature limit is clearly constrained by β-grain growth, necessitating a study of its temperature dependence.

To determine quenching temperatures, the alloy was heated after forging in the temperature range of 950—1100 °C with a holding time of 2 h. At t = 950 °C, the β-phase grain size increased to 2 μm, and the particle size was 1 μm (Fig. 6, *a*). Heating to 975 °C resulted in

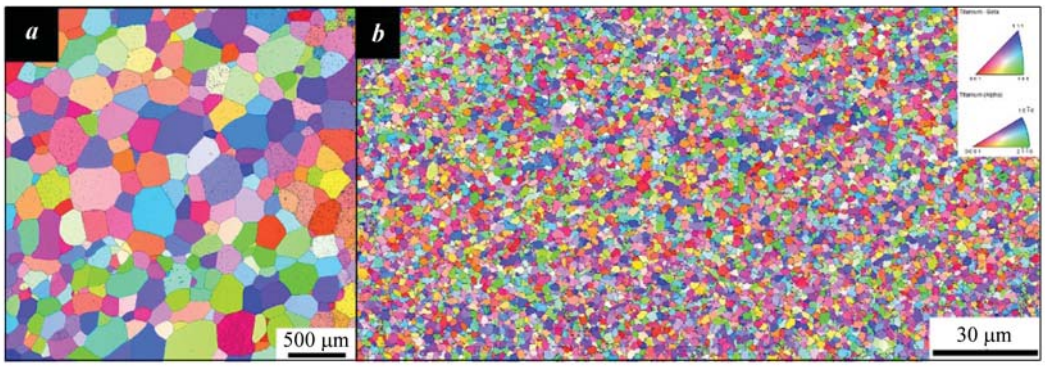

Fig. 5. Microstructure of epy VIT1 alloy after annealing at t = 1100 °C for 0.5 h (EBSD IPF map) (***a***) and after multi-directional isothermal forging at t = 950 °C, strain rate of 10^{-3} s^{-1}, and accumulative strain of 750 % (***b***)

Рис. 5. Микроструктура сплава ВИТ1 после отжига при t = 1100 °C, τ = 0,5 ч (EBSD IPF-карта) (***a***) и после всесторонней изотермической ковки при t = 950 °C, скорости деформации 10^{-3} $с^{-1}$, накопленной степени деформации 750 % (***b***)

complete dissolution of the O-phase and a reduction in the α_2-phase volume fraction from 13 to 11 vol. % (Fig. 6, *b*). The β-phase grain size increased to 4 μm, while the α_2-phase particle size remained unchanged. After heating to 1000 °C, the β-phase grain size increased to 6 μm (Fig. 6, *c*), and at 1025 °C, it reached 8 μm (Fig. 6, *d*). At these temperatures, the α_2-phase fraction decreased to 5 and 3 vol. %, respectively. Further temperature increases to 1050 and 1075 °C caused a sharp growth in β-phase grains to 50 and 100 μm, respectively, while the α_2-phase volume fraction decreased to 1—2 vol. % (Fig. 6, *e*, *f*). Complete dissolution of the α_2-phase was observed after heating and holding at 1100 °C, where the average β-phase grain size reached 200 μm (Fig. 6, *f*).

Hus, as the heating temperature for quenching increases within the range of 950—1025 °C, a gradual increase in β-grain size from 4 to 8 μm is observed. However, heating to 1050—1100 °C results in a sharp growth of β-grains due to a reduction in the α_2-phase fraction. A quenching temperature of 975 °C was preliminarily selected for determining the aging conditions.

Fig. 7 shows the evolution of the microstructure of the quenched VIT1 alloy during aging at t = 750, 800, and 850 °C for 0.5, 6, 48, and 192 h. It can be observed that, with increasing aging time, needle-shaped O-phase particles precipitate within the β-phase and form interlayers along the grain boundaries. The lower the aging temperature, the thinner the O-phase particles at all holding times (Table 1, Fig. 7). As the holding time increases, coarsening and spheroidization of the O-phase particles are observed, and, at longer holding times, some α_2-phase particles transform into the O-phase [20; 21] (Fig. 7, *g*—*l*). Thus, it was established that during aging, O-phase particles of varying dispersion precipitate, with dispersion decreasing as both temperature and holding time increase.

The change in the microhardness of the alloy correlates with the evolution of its microstructure during aging (Fig. 8). The formation of fine acicular O-phase particles at the initial stage of aging (τ = 0.5 h) leads to a sharp strengthening of the quenched alloy, with a greater effect observed at lower temperatures. With a further increase in aging time (τ > 1 h), softening occurs due to the coarsening of the O-phase particles. However, after τ > 4 h, the microhardness changes only slightly. The most significant decrease in microhardness is observed after aging times exceeding 48 h at all temperatures. This is likely due to the continued coarsening and spheroidization of the O-phase particles, along with the transformation of $\alpha_2 \rightarrow$ O. The fact that the microhardness of the alloy stabilizes after the initial softening suggests a certain structural stabilization at this stage of aging. Based

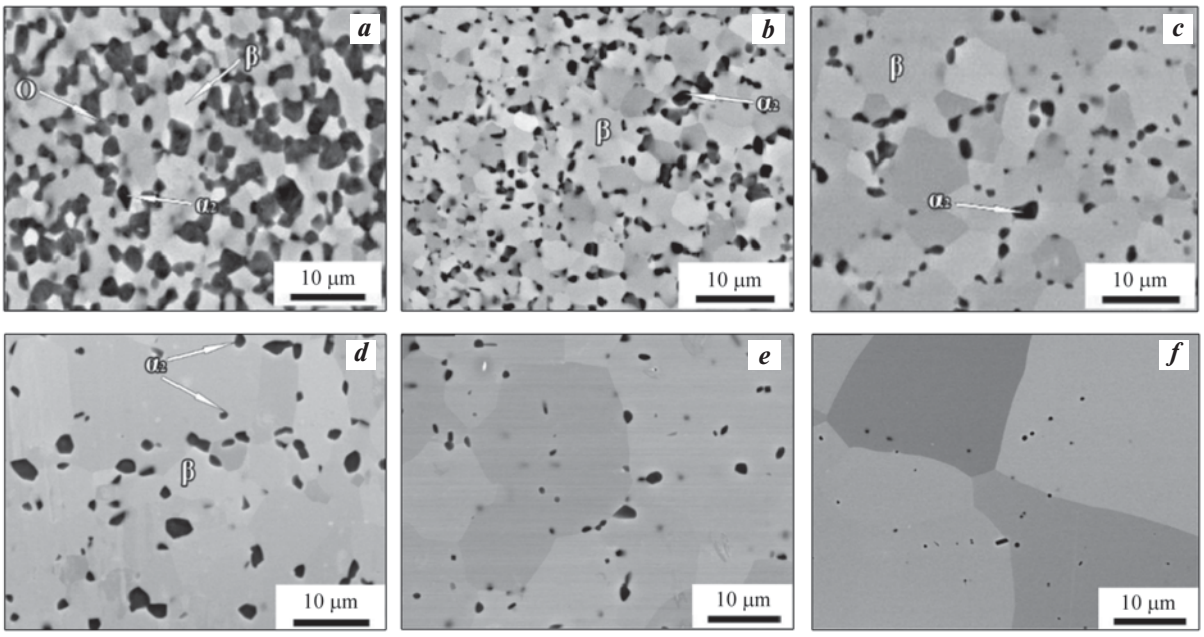

Fig. 6. Microstructure of the VIT1 alloy forged under isothermal conditions and quenched at various temperatures (SEM)
t, °C: ***a*** – 950, ***b*** – 975, ***c*** – 1000, ***d*** – 1025, ***e*** – 1050, ***f*** – 1075

Рис. 6. Микроструктура кованного в изотермических условиях сплава ВИТ1 после закалки при различных температурах (СЭМ)
t, °C: ***a*** – 950, ***b*** – 975, ***c*** – 1000, ***d*** – 1025, ***e*** – 1050, ***f*** – 1075

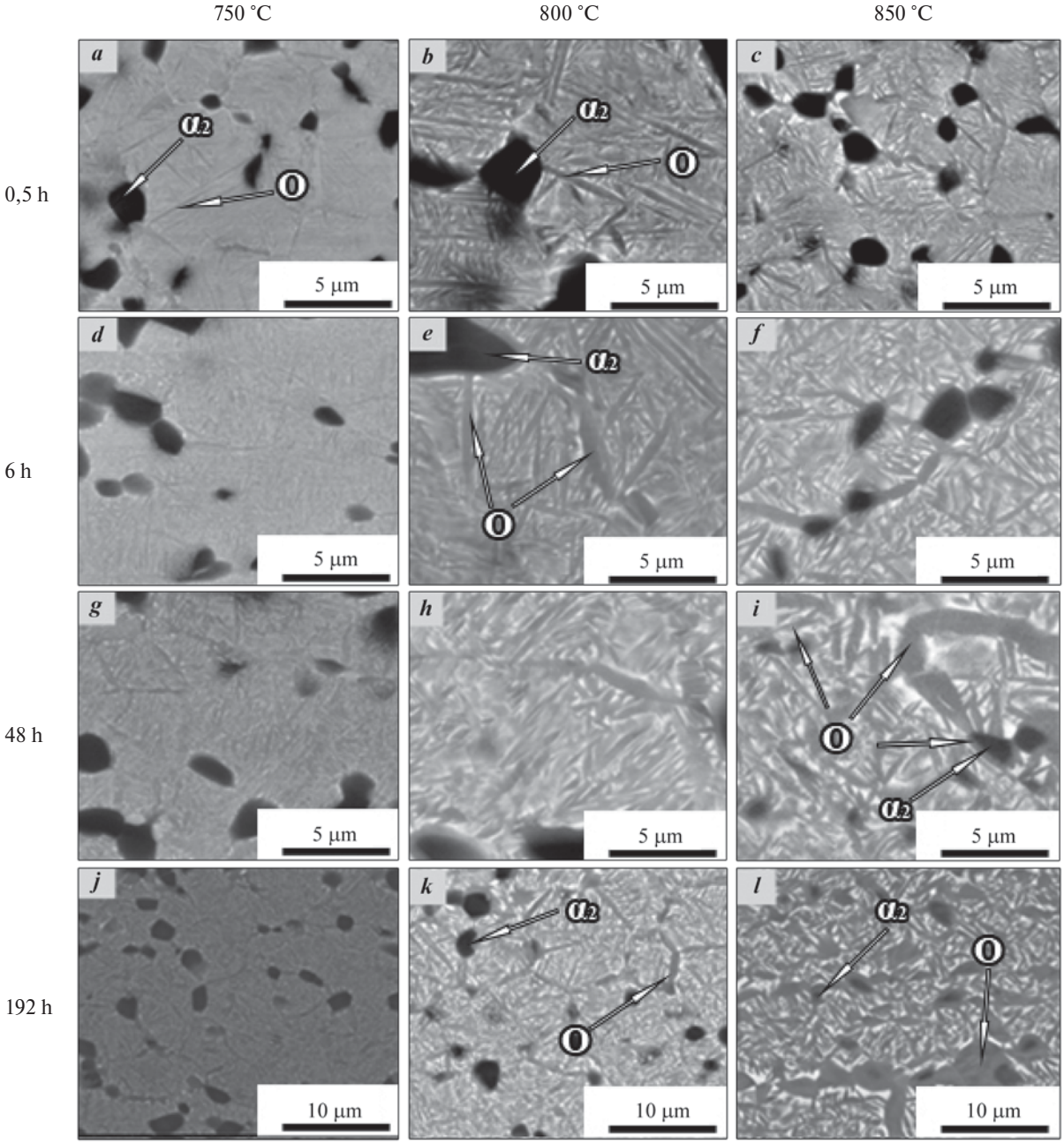

Fig. 7. Microstructure of the VIT1 alloy after quenching at t = 975 °C and aging (SEM)

Рис. 7. Микроструктура сплава ВИТ1 после закалки с t = 975 °C и старения (СЭМ)

on these findings, an aging time of 6 h was selected for further studies.

The results of tensile testing for the alloy after heat treatment (quenching at t = 975 °C, holding for 2 h, and aging at t = 750, 800, and 850 °C for 6 h [22]) are presented in Table 2. It is evident that the lowest aging temperature corresponds to the highest strength (σ_u = 1450 MPa) and the lowest ductility (δ = 2 %). Increasing the aging temperature to 800 °C slightly reduces the yield strength but significantly increases ductility to 6.2 %. Further increasing the aging temperature to 850 °C reduces σ_u to 1200 MPa while raising δ to 8.0 %. Meanwhile, creep testing at t = 650 °C and σ = 380 MPa for the alloy aged at t = 800 °C revealed a time-to-failure of only τ = 40 h. This short time-to-failure is evidently related to the small β-grain size (4 μm) in this alloy state (Table 2).

Therefore, additional studies were conducted to evaluate the mechanical properties of the alloy with larger β-grain sizes. To achieve coarser grains, the quenching temperature was increased to 1000 and 1025 °C, while the aging temperature was maintained at 850 °C to

Table. 1. **Thickness of O-phase particles after quenching at t = 975 °C and aging**

Таблица 1. Толщина частиц О-фазы после закалки с t = 975 °C и старения

t, °C	Thickness of O-phase particles, nm, at τ, h					
	0,5	6	12	48	96	192
750	65 ± 15	68 ± 25	70 ± 30	95 ± 35	100 ± 30	120 ± 50
800	70 ± 20	100 ± 30	130 ± 40	150 ± 40	180 ± 50	230 ± 100
850	75 ± 35	120 ± 70	160 ± 75	190 ± 20	240 ± 111	310 ± 120

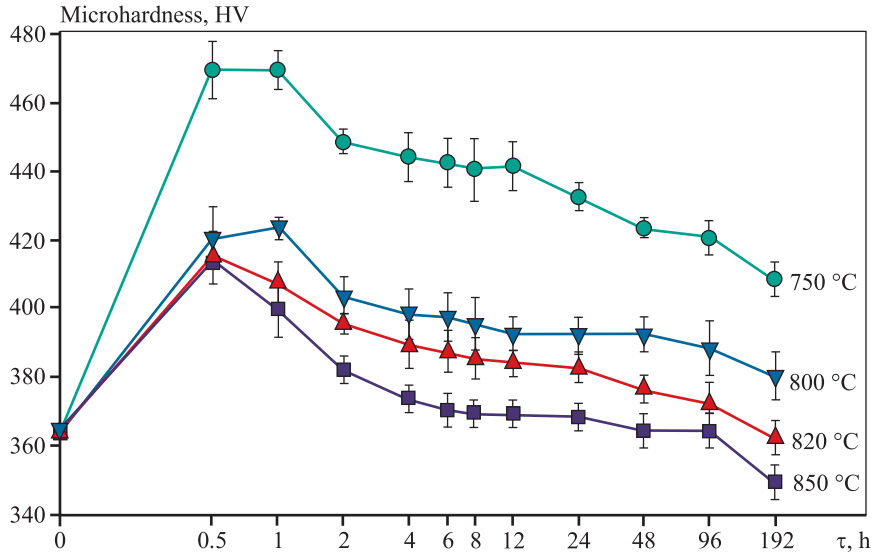

Fig. 8. Dependence of the microhardness of the VIT1 alloy after quenching (t = 975 °C) and aging (t = 750÷850 °C) on holding time

Рис. 8. Зависимость микротвердости сплава ВИТ1 после закалки (t = 975 °C) и старения (t = 750÷850 °C) от времени выдержки

compensate for the loss of ductility (Table 2). The most balanced combination of strength (σ_u = 1260 МПа), ductility (δ = 5.8 %), and time-to-failure (299 h) was observed with a β-grain size of 12 μm, achieved after heat treatment under the following conditions: quenching at t = 1025 °C, holding for 4 h, and aging at t = = 850 °C for 6 h. The obtained mechanical properties surpass those reported in [1; 2], where the VIT1 alloy subjected to multi-stage forging and rolling followed by heat treatment demonstrated σ_u = 1150 MPa and δ = = 4 %. A clear advantage of using multi-directional isothermal forging as a preliminary processing step is the significant improvement in hot ductility, which is characteristic of fine-grained alloys [23—26].

Conclusions

1. The effect of hot deformation by uniaxial compression in the temperature range of 850—1050 °C on the mechanical behavior and structural evolution of the VIT1 alloy in a hot-rolled coarse-grained state was investigated. It was shown that the most intense microstructure refinement (average grain size ~1 μm) occurs in the (α_2 + β + O)-phase region at 950 °C due to active dynamic recrystallization and spheroidization. As the temperature increases and transitions into the (α_2 + β)-phase region, the activation of dynamic recovery, caused by the dissolution of O-phase particles, reduces the degree of microstructure refinement.

2. Multi-directional isothermal forging of hot-rolled VIT1 billets at 950 °C with a total strain of 750 % produced forgings with a homogeneous fine-grained structure (~1 μm grain size). It was demonstrated that the uniformity of the microstructure could be improved by preliminary annealing at 1100 °C. The temperature dependence of grain size in fine-grained billets revealed a gradual increase from 4 to 8 μm in the range of 950—1025 °C (2-hour hold), with a sharp growth to

Table. 2. **Mechanical properties of the VIT1 alloy after forging and heat treatment**

Таблица 2. Механические свойства сплава ВИТ1 после ковки и термической обработки

Heat treatment			Size of β-grains, μm	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	Time-to-failure, h, at t = 650 °C and σ = 380 MPa
t_{quen}, °C	t_{aging}, °C	τ, h					
975	750	2 6	4	1340 ± 25	1450 ± 30	2.0 ± 0.2	–
975	800	2 6	4	1280 ± 20	1420 ± 30	6.2 ± 0.3	40
975	850	2 6	4	1020 ± 20	1200 ± 25	8.0 ± 0.5	–
1000	800	2 6	6	1230 ± 30	1350 ± 35	6.0 ± 0.4	100
1025	800	2 6	8	1200 ± 30	1300 ± 30	5.9 ± 0.4	170
1025	850	4 6	12	1180 ± 30	1260 ± 30	5.8 ± 0.3	299

50 μm at 1050 °C and further to 200 μm at 1100 °C, due to a reduction in the volume fraction of α_2-phase particles.

3. The changes in microhardness and the evolution of microstructure during the aging of the quenched alloy were studied. It was found that the formation of fine acicular O-phase particles at the initial stage leads to a sharp strengthening of the quenched alloy, with a greater effect observed at lower temperatures. Prolonged aging results in softening caused by the coarsening and spheroidization of O-phase particles, as well as α_2-phase degradation due to the $\alpha_2 \rightarrow O$.

4. Based on the conducted studies, the quenching temperature range (975—1025 °C) and aging temperature range (750—850 °C) were selected to ensure a balance of strength, ductility, and heat resistance in the alloy processed by multi-directional isothermal forging. Mechanical testing results indicate that quenching at 1025 °C with a 4-hour hold, followed by aging at 850 °C for 6 h, provides the most balanced combination of strength ($\sigma_{0.2}$ = 1180 MPa, σ_u = 1260 MPa), ductility (δ = 5.8 %), and heat resistance (time-to-failure of 299 h at 650 °C and 380 MPa).

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Yu.G. Bykov – analyzed the effect of processing conditions on the mechanical properties of the alloys, participated in result discussions.

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